Wave-particle interaction in space and Tokamak plasmas

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Outline

- Whistler wave-electron interaction in radiation belt
  - Quasilinear theory application: diffusion equation
  - Bounce-averaged diffusion equation for energetic particles in an arbitrary magnetic field
- Electron test particle simulation in a whistler wave: beyond quasilinear theory. $\longrightarrow$ Wave amplitude
- Anomalous electron-ion energy coupling in drift wave turbulence
- Drift waves can mediate the energy transfer between electron and ion through wave-particle interaction.
- Two nonlinear energy coupling channels
  - Turbulence and zonal flow interaction
  - Nonlinear wave-particle interaction
- Conclusion

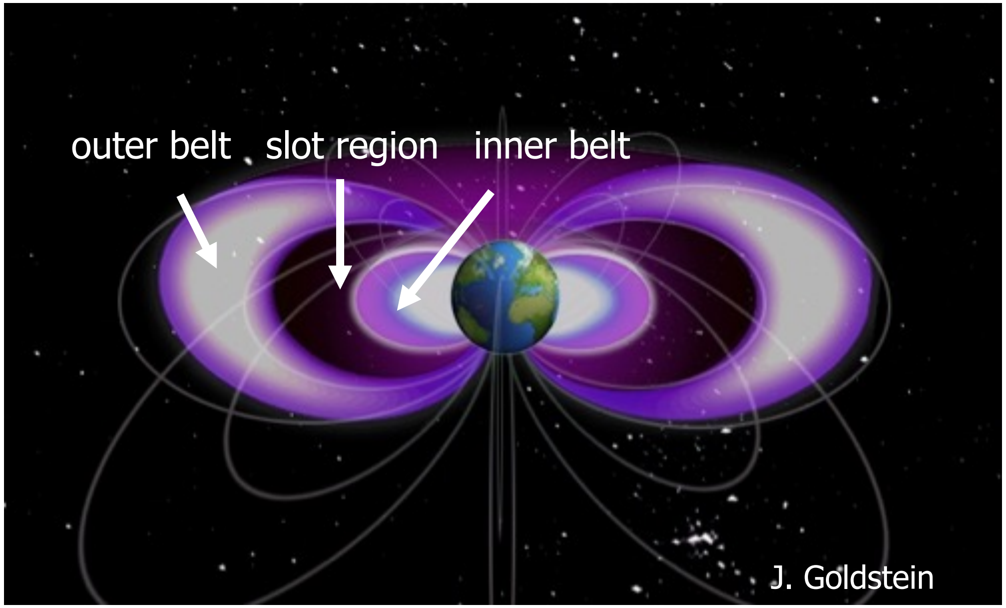
Wave-particle interaction in space plasma (I)

- Investigating the whistler-electron interaction in radiation belts

- Magnetic field geometry play an important role in wave-particle resonance

Background

- Discovery of Van Allen Radiation Belts - Explorer, 1958
- Trapped electrons and ions
  Spatial distribution: 2-7 R_E
  Energy: Mev



Pickering, Van Allen & Von Braun IGY News conference at National Academy Science in Washington D.C.

Charged Particle Motion in Magnetosphere

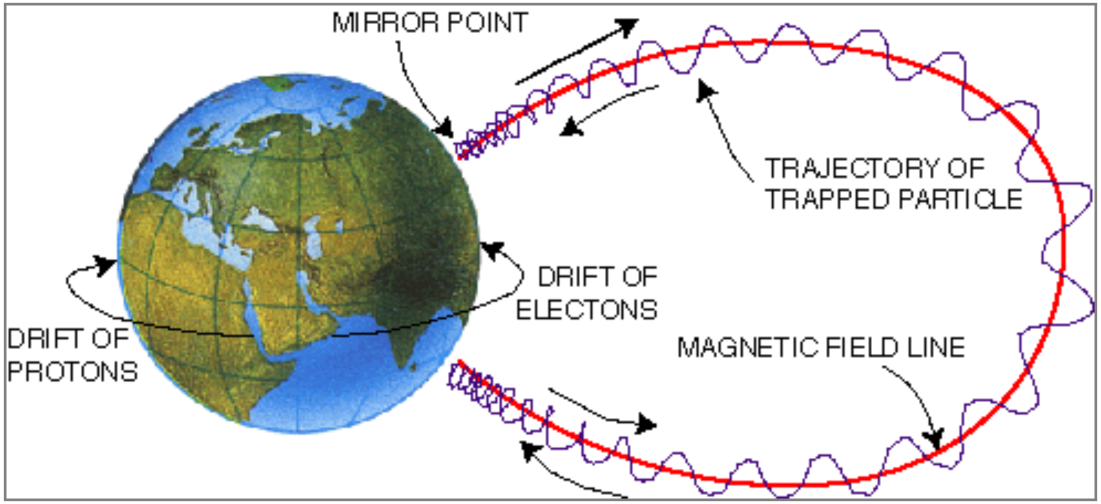
- Three motions: Gyro, bounce and drift motions

- Adiabatic invariant and L-shell

$$\mu = \frac{W_\perp}{B}$$ Magnetic moment

$$J = \int p_{\|} ds$$ Integral invariant

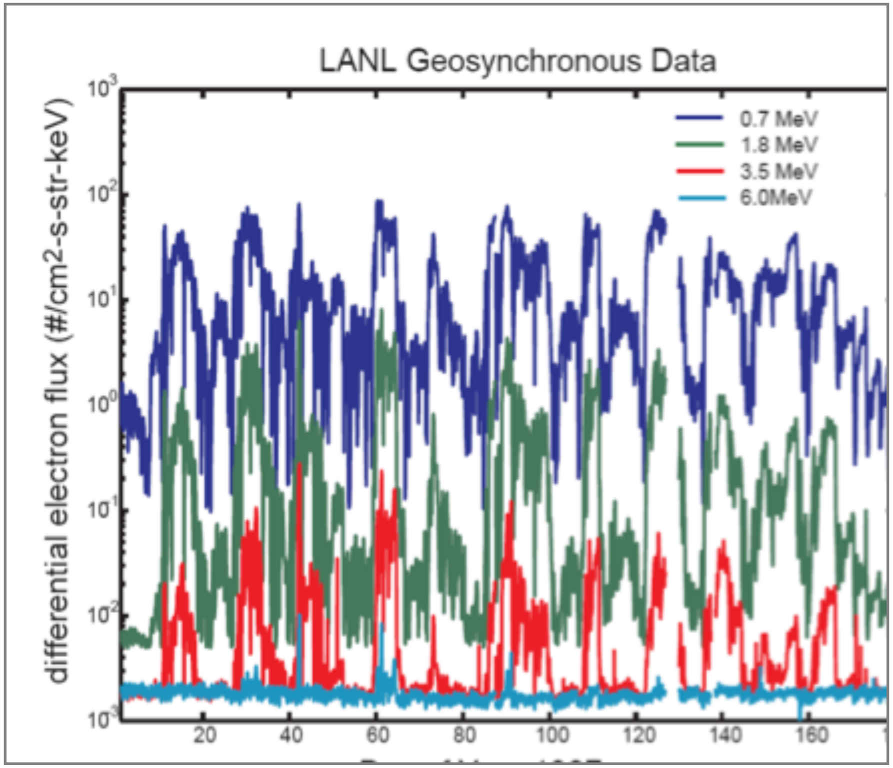
$$\Phi = \oint B dS$$ Magnetic flux



Trajectory of trapped electrons and protons experiencing magnetic mirroring and gradient and curvature drifts in the geomagnetic field.

- Wave with frequency comparable to or exceeding the characteristic frequency will break the relevant adiabatic invariant and lead to particle diffusion.

Dynamics of energetic particles in radiation belts



(Green, 2002)

- Resonant wave-particle interaction play an important role in processes of transport,acceleration and loss of particles

Transport: particle, energy,momentum

Acceleration: heating by Whistler waves

Loss: pitch-angle diffusion

- Quasilinear diffusion equation

To quantify the rates of particle energy diffusion and pitch angle scattering due to cyclotron resonant interaction with whistler wave,the diffusion coefficients need to be given

Pitch-angle, energy, mixed term diffusion coefficients

Quaslinear diffusion equation

- Quasilinear theory application: *(Kennel 1966, Lyons 1973)*
  - The Vlasov equation:

$$\frac{\partial f^{\pm}}{\partial t} + \vec{v}\cdot\vec{\nabla} f^{\pm} \pm \frac{e}{m_{\pm}}(\vec{E} + \frac{\vec{v}\times\vec{B}}{c})\frac{\partial f^{\pm}}{\partial v} = 0$$

+:ion -:electron

$f = \langle f \rangle + \tilde{f},\quad E = \langle E \rangle + \tilde{E},\ B = \langle B \rangle + \tilde{B}$

Fourier transform $\tilde{f}, \tilde{E}, \tilde{B}$

Take a space average of Vlasov equation to obtain the quasilinear diffusion equation for $\langle f \rangle$

- A general Diffusion equation in a spherical coordinates:

$$\frac{\partial f}{\partial t} = \frac{1}{\sin\alpha}\frac{\partial}{\partial\alpha}\sin\alpha\left(D_{\alpha\alpha}\frac{\partial f}{\partial\alpha} + D_{\alpha v}\frac{\partial f}{\partial v}\right) + \frac{1}{v^2}\frac{\partial}{\partial v}v^2\left(D_{v\alpha}\frac{1}{v}\frac{\partial f}{\partial\alpha} + D_{vv}\frac{\partial f}{\partial v}\right)$$

Valid for any modes of weak turbulence in uniform,static magnetic field

Pitch-angle: $D_{\alpha\alpha} = \sum_{n=-\infty}^{\infty}\int_0^{\infty} k_\perp dk_\perp D_{\alpha\alpha}^{nk_\perp}$

Mixed term: $D_{\alpha v} = D_{v\alpha} = \sum_{n=-\infty}^{\infty}\int_0^{\infty} k_\perp dk_\perp D_{\alpha v}^{nk_\perp}$

Speed: $D_{vv} = \sum_{n=-\infty}^{\infty}\int_0^{\infty} k_\perp dk_\perp D_{vv}^{nk_\perp}$

- Wave-particle resonance condition: $k_{\parallel} = (\omega_k - n\Omega)/v_{\parallel}$
  - Landau resonance: $n = 0$
  - Cyclotron resonance : $n = \pm 1, \pm 2; \cdots$

Relativistic diffusion equation (Summers,2005)

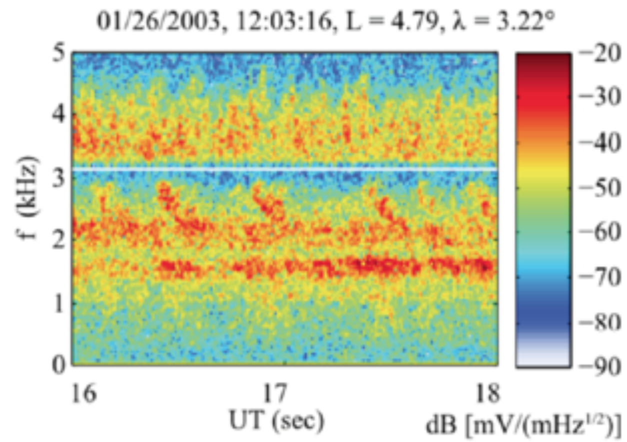
- Assume an infinite,homogenous, collisionless plasma immersed in a uniform, static magnetic field $\vec{B}_0 = B_o \hat{e}_z$

- The general quasilinear diffusion equation in the relativistic regime

$$\frac{\partial f}{\partial t} = 2\pi q^2 \lim_{v\to\infty} \frac{1}{(2\pi)^3 V} \int d^3k \sum_{n=-\infty}^{\infty} \frac{1}{p_\perp} \hat{G} p_\perp |\theta_n|^2 \delta(\omega - k_\parallel v_\parallel - \frac{n\Omega}{\gamma}) \hat{G} f$$

–Transform $\hat{G}$ from $(p_\perp, p_\parallel)$ to (p,u) $, p_\perp = p(1-u)^{1/2}, p_\parallel = pu, u = \cos\alpha$

– Resonance condition: $\omega - k_\parallel v_\parallel - \frac{n\Omega}{\gamma} = 0$



$$\Rightarrow \frac{\partial f}{\partial t} = \frac{\partial}{\partial u}\left(D_{uu}\frac{\partial f}{\partial u}\right) + \frac{\partial}{\partial u}\left(D_{up}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pu}\frac{\partial f}{\partial u}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial u}\right)$$

Whistler wave dispersion relations:

$$\frac{y^2}{x^2} = 1 - \left(\frac{\omega_{pe}}{\Omega_e}\right)^2 \frac{1+\epsilon}{(x-1)(x+\epsilon)}.$$

Pitch angle diffusion coefficient: $D_{\alpha\alpha} = D_{uu}/\sin^2\alpha = \frac{\pi}{2}\frac{1}{V}\frac{\Omega_\sigma^2}{|\Omega_e|}\frac{1}{(E+1)^2}\sum_s\sum_j \frac{R(1 - x\cos\alpha / y\beta)}{\delta x}\frac{|F(x,y)|}{|\beta\cos\alpha - F(x,y)|}$

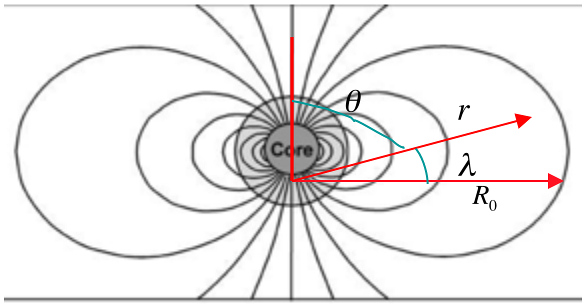
Renormalization factor: $x = \frac{\omega}{|\Omega_e|}$, $y = \frac{ck}{|\Omega_e|}$, $F(x,y) = \frac{d\omega}{cdk}$, $R = \frac{\Delta B^2}{B_0^2}$, $E = \frac{E_k}{mc^2} = \gamma - 1$

Similarly: $D_{p\alpha} = D_{\alpha P}$ and D_{pp}

Bounce-averaged diffusion equation

• How to describe the dynamics of the energetic particles trapped in the Earth's magnetosphere?

Bounce-averaged Diffusion equation
- Local diffusion tensor
- Bounce-average the diffusion coefficients in a trapped motion



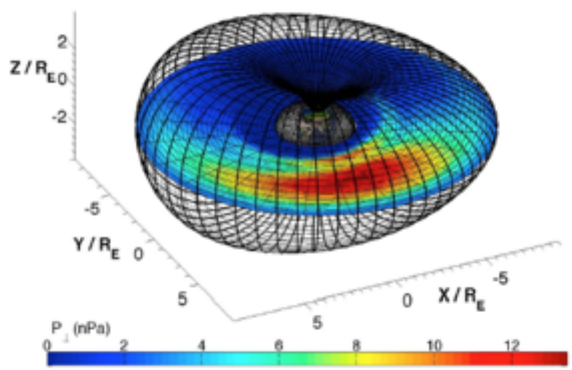
• The bounce-averaged diffusion coefficients in a dipole/non -dipole magnetic field

Pitch angle:

$$\langle D_{\alpha\alpha}(\alpha_{eq})\rangle_b = \frac{\int_{\lambda_1}^{\lambda_2} D_{\alpha p}(\alpha,\lambda)\left(\frac{\tan\alpha_{eq}}{\tan\alpha(\lambda)}\right)^2 \sec\alpha(\lambda)\sqrt{\left(\frac{\partial r}{\partial\lambda}\right)^2 + r^2}\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \sec\alpha(\lambda)\sqrt{\left(\frac{\partial r}{\partial\lambda}\right)^2 + r^2}\,d\lambda},$$

Energy:

$$\langle D_{pp}(\alpha_{eq})\rangle_b = \frac{\int_{\lambda_1}^{\lambda_2} D_{pp}(\alpha,\lambda)(\sec\alpha(\lambda)\sqrt{\left(\frac{\partial r}{\partial\lambda}\right)^2 + r^2}\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \sec\alpha(\lambda)\sqrt{\left(\frac{\partial r}{\partial\lambda}\right)^2 + r^2}\,d\lambda}$$



• RAM-SCB model: driven by highly variable solar wind

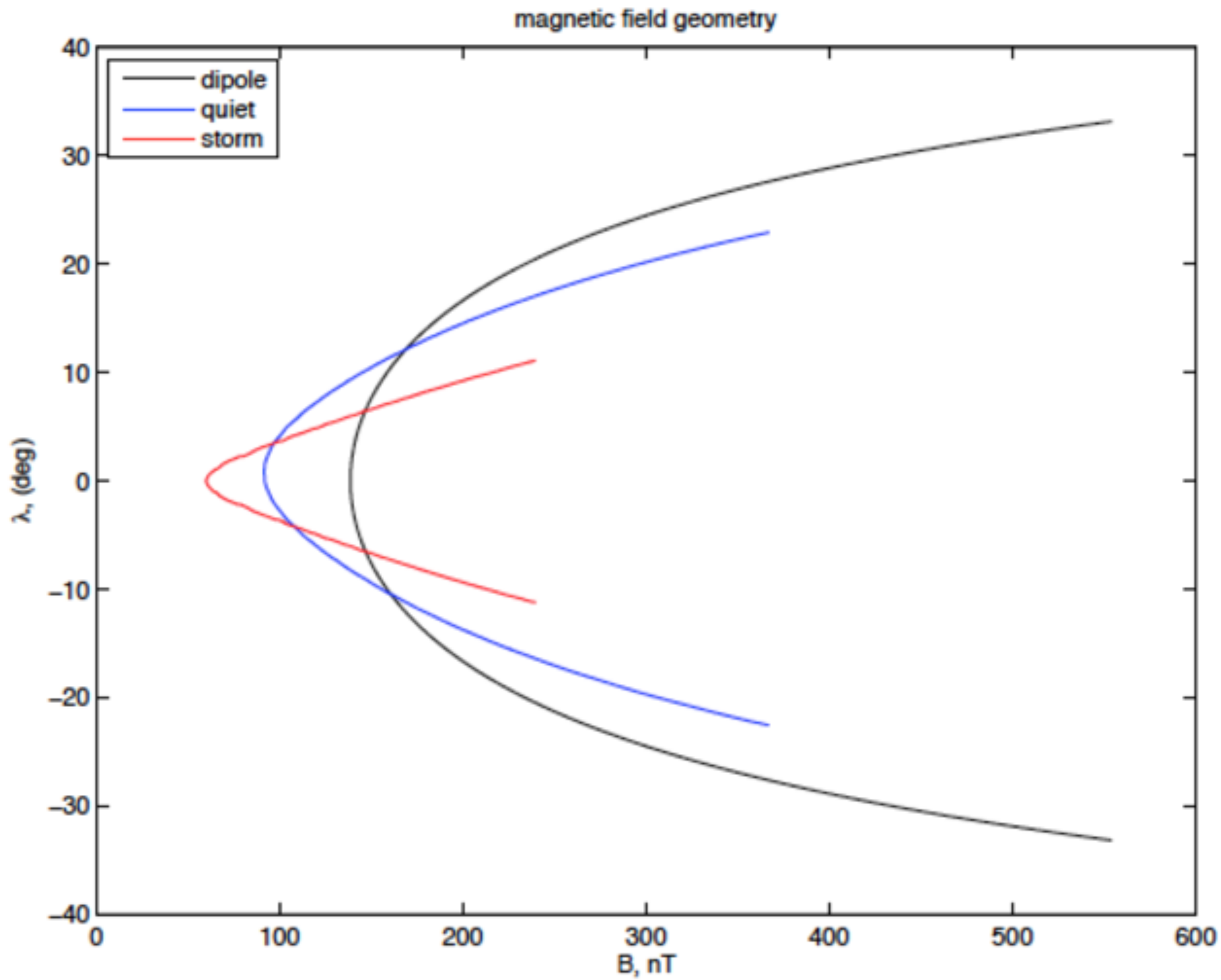
– 3D magnetic field, more realistic $B(\lambda)$, $r(\lambda)$, $\frac{\partial r}{\partial \lambda}$

– Calculate diffusion rates during storms, assess role of magnetic field geometry

RAM-SCB models the region inside geosynchronous orbit. The black line is magnetic field line.

(Jordanova 2010, Zaharia 2010)

Magnetic field geometry described by RAM-SCB



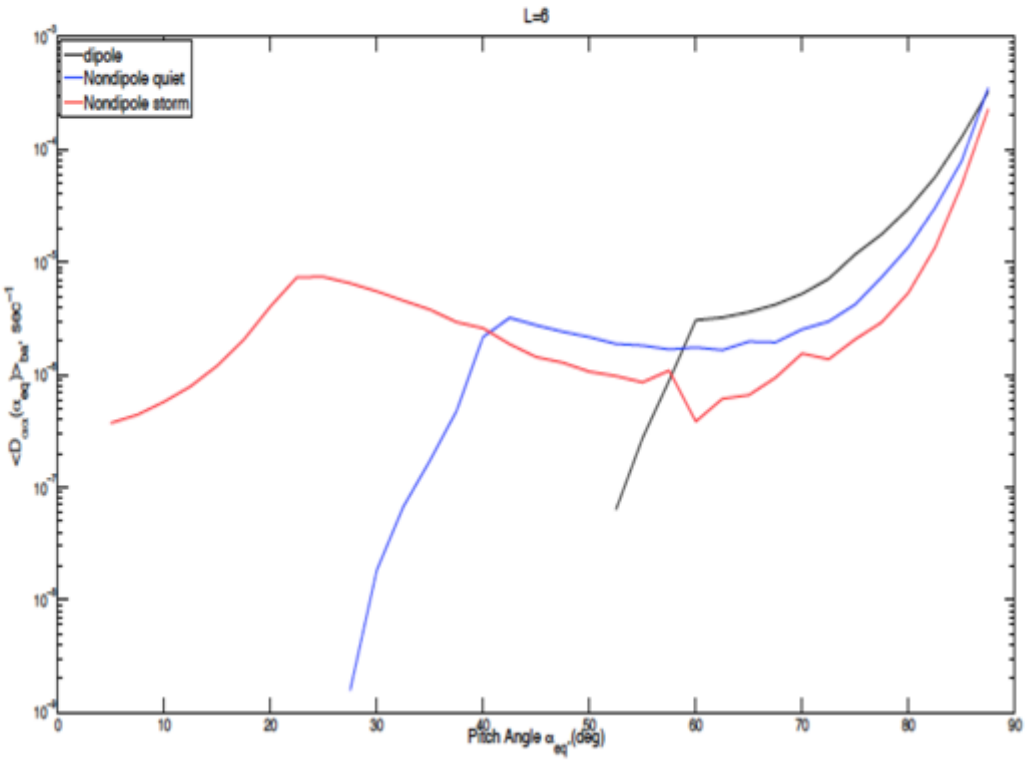
MLT=24

L=R_o/R_E

• Magnetic field magnitude along the field line versus magnetic latitude L=6 obtained by RAM-SCB modeling of the 17 March 2013 Storm for nightside Storm(red line, UT=8), Quiet(blue line, UT=4) and Dipole(black line) field model. The equatorial pitch angle is $\alpha_{eq} = 30^0$

Results: Bounce-averaged pitch-angle diffusion coefficients

(Lei Zhao *et al*., JGR, 2015)



- Near the edge of the loss cone, the electron scattering rate is biggest for the magnetic field model in storm condition compared to the other two cases. Electron can easily be lost in a storm condition through pitch angle scattering.

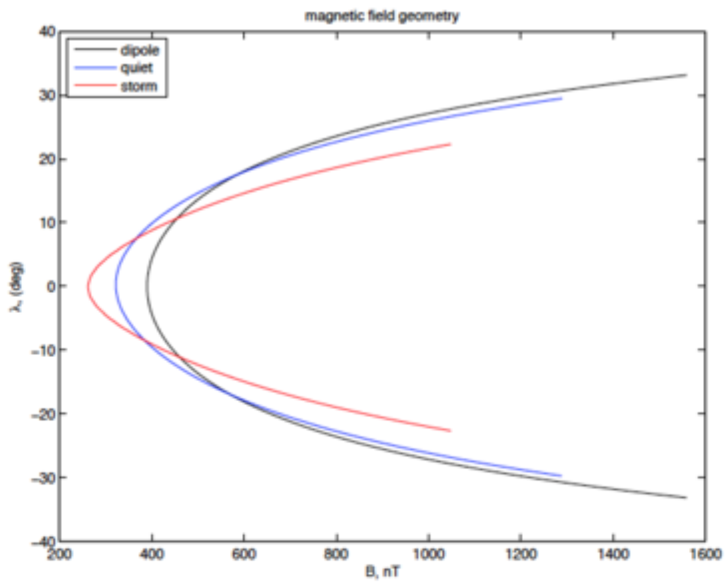
- In the large equatorial pitch angle, electron pitch angle scattering rate in three cases are consistent with.

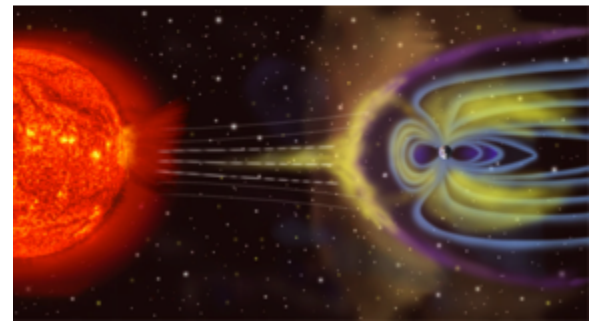
- Bounce-averaged pitch-angle diffusion coefficients as a function of equatorial pitch angle.

•Parameters: L=6, $n_e = 5cm^{-3}$ $\omega_m = 0.35\Omega_{eq}$ $\delta\omega = 0.2\Omega_{eq}$ $\lambda_{\max} = \pm 15^0$

Detail: March 17, 2013 storm

- Magnetic field geometry at L=4.25, MLT=24, 20, 16, 12, 8 and 4 of March 17, 2013 storm.





The Earth's magnetosphere is compressed on the Sun side and stretch out on the night side.

- Wave spectrum and plasma parameters at L=4.25, for various magnetic local times (MLTs)

	ω_m/Ω_{ce}	$\delta\omega/\Omega_{ce}$	$\lvert\lambda\rvert$	$n_e(cm^{-3})$	$< B_w > (pT)$
04 MLT	0.25	0.1	$< 10°$	9.3	100
08 MLT	0.23	0.1	$< 15°$	9.5	100
12MTL	0.21	0.08	$< 45°$	13.5	100
16MTL	0.2	0.08	$< 45°$	17.4	100
20MLT	0.2	0.06	$< 25°$	17.2	100
24MLT	0.22	0.08	$< 10°$	13.1	100

- Wave spectral density: Gaussian distribution

ω_m wave spectrum peak value

$\delta\omega$ semi bandwidth

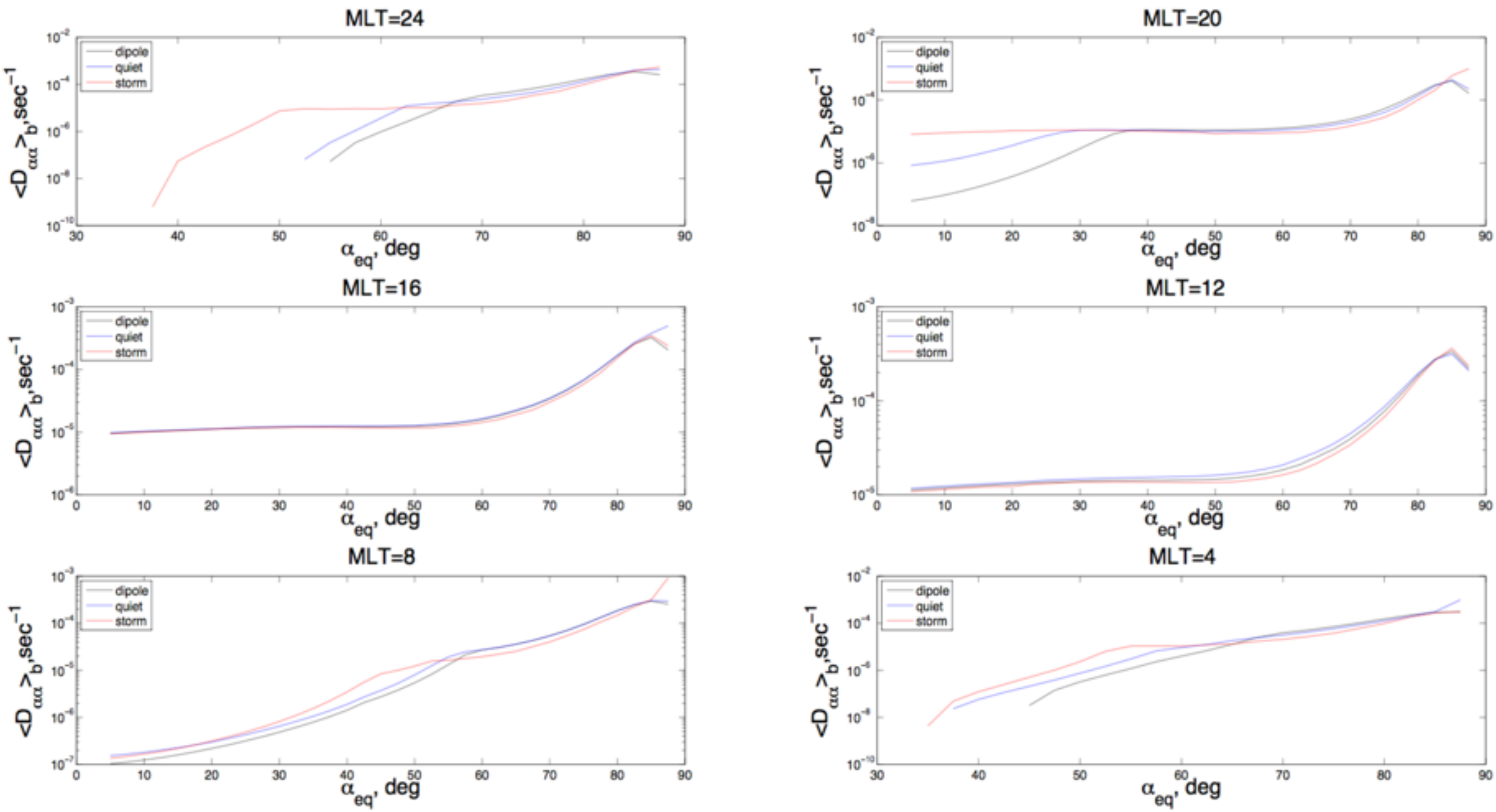
Ω_{ce} electron cyclotron frequency

λ wave latitude extension

n_e electron density

$\langle B_w \rangle$ average chorus wave amplitude

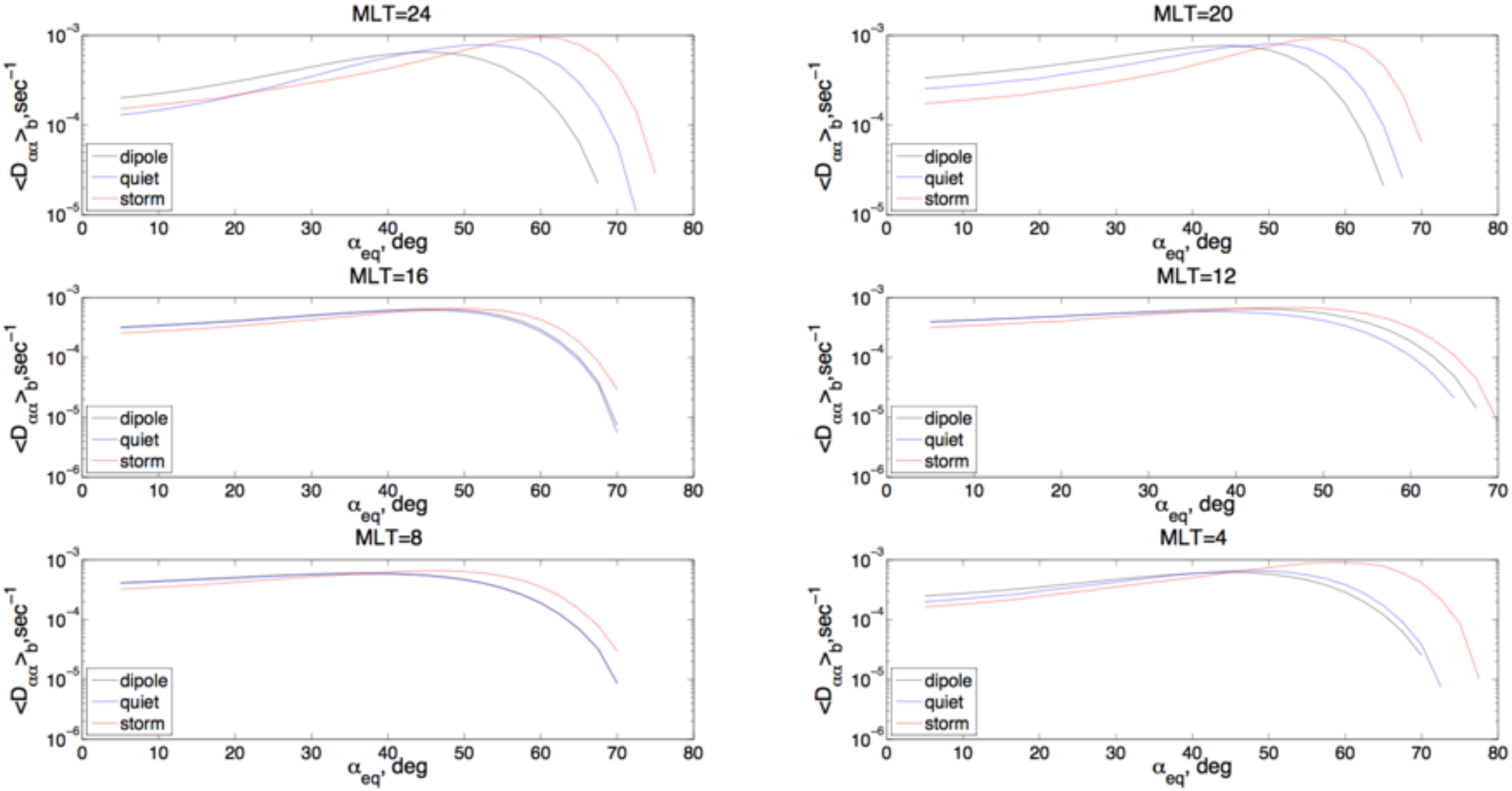
• Relativistic electrons: Pitch angle diffusion at E=1Mev



• At nightside MLTs 24, 20 and 4, pitch angle scattering extends to smaller equatorial pitch angles in storm condition.

• At dayside MLTs 16,12 and 8, pitch angle scattering tends to be insensitive to magnetic field geometry and the scattering rates are consistent in dipole, storm and quiet of March 17 storm conditions.

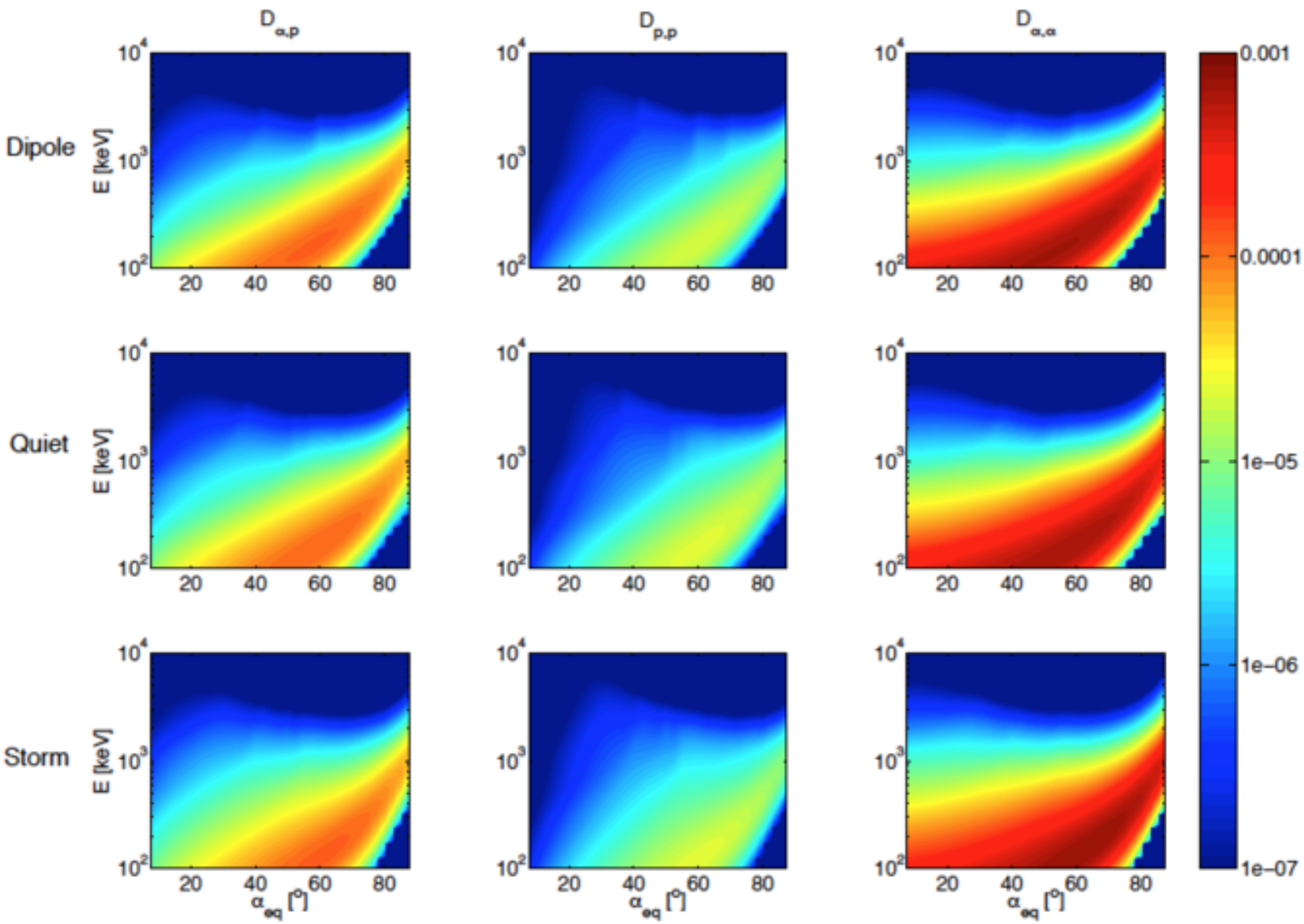
- Lower energy electrons: Pitch angle diffusion at E=100Kev



- At night side MLTs 24, 20 and 4, the pitch angle scattering rate is significantly enhanced at larger equatorial pitch angles in storm condition. This will influence the electron density distribution and the electron flux evolution.

- At day side MLTs 16,12 and 8, the pitch angle scattering rate is slightly bigger in storm condition than in the other two cases for larger equatorial pitch angles. The magnetic field geometry effect is not that important.

Bounce - and MLT-averaged diffusion



a). Diffusion coefficients $D_{\alpha\alpha}, D_{\alpha p}, D_{pp}$ increase with lower electron energy and larger equatorial pitch angles.

b). $D_{\alpha\alpha} > D_{\alpha p} \geq D_{pp}$

Mixed term diffusion plays significant role in the energy diffusion process

- Bounce- and MLT- averaged pitch angle, energy and mixed term diffusion coefficients as a function of equatorial pitch angle α_{eq} and electron energy (E) at L=4.25 for three magnetic field configurations. Electron kinetic energy range is from 100KeV to 10MeV.

- Magnetic field geometry effect are more important for energy below 1MeV electrons.

Wave-particle interaction in space plasma (II)

- Electron test particle simulation in a whistler wave: beyond quasilinear theory

- Breakdown QL : large wave amplitude

Comparison: Test Particle Model vs quasilinear theory

- Test particle model : need EM field (wave) to move particles
  - Particle: $\frac{d\mathbf{x}}{dt} = \frac{\mathbf{p}}{\gamma m}; \quad \frac{d\mathbf{p}}{dt} = q[\mathbf{E}_w + \frac{\mathbf{p}}{\gamma m}(\mathbf{B}_w + \mathbf{B}_0)$
  - Whistler wave: $\mathbf{E}_w = \sum_{j=1}^{N_w} -E^w_{xj}\sin\phi_j\hat{e}_x - E^w_{yj}\cos\phi_j\hat{e}_y; \quad \mathbf{B}_w = \sum_{j=1}^{N_w} -B^w_{xj}\cos\phi_j\hat{e}_x - B^w_{yj}\sin\phi_j\hat{e}_y$
  - Set up parameters: $N_{wave} = 4000, \quad N_{particle} = 2000, \quad W_s(\omega) \propto e^{-\left(\frac{\omega - \omega_m}{\delta\omega}\right)^2}$

    $B_0 = 1.4 \times 10^{-7} T, \quad \omega \in (0.2, 0.4)\Omega_{ce}, \quad \delta\omega = 0.05\Omega_e$
  - Test particle pitch angle diffusion coefficients in linear phase: $D^{TP}_{uu} = \frac{\langle \Delta u^2 \rangle}{2\Delta t} \qquad \mu = \cos\alpha$
- Particle pitch angle diffusion coefficients from the quasilinear theory

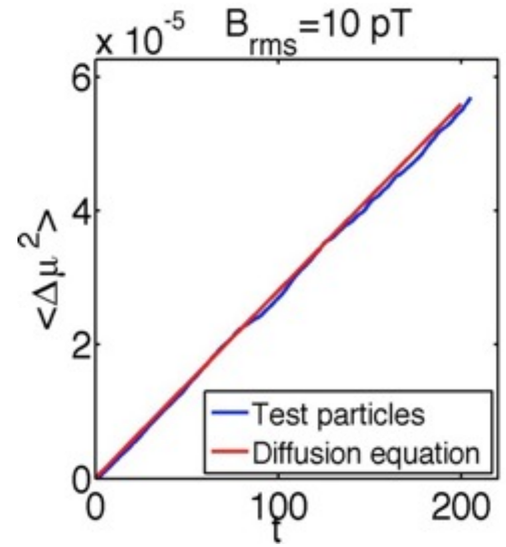
$$D_{\alpha\alpha} = \frac{\pi}{2}\frac{1}{V}\frac{\Omega_\sigma^2}{|\Omega_e|}\frac{1}{(E+1)^2}\sum_s\sum_j \frac{R(1 - x\cos\alpha / y\beta)}{\delta x}\frac{|F(x,y)|}{|\beta\cos\alpha - F(x,y)|}$$

(Summers,2005)

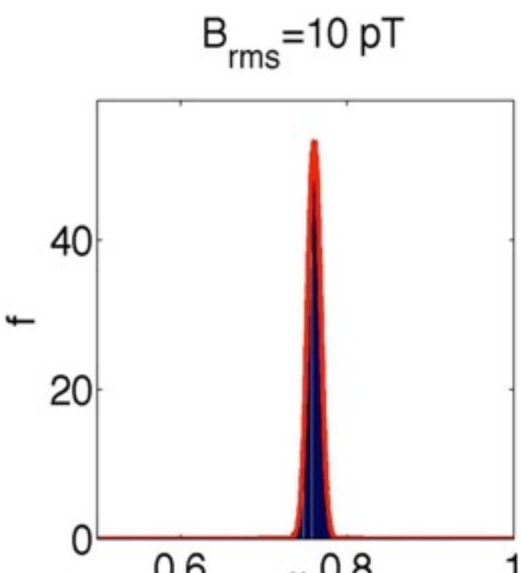
Pitch angle diffusion at small wave amplitude

(Lei Zhao, Gian Luca Delzanno, et al GEM workshop 2015)

- Small whistler wave amplitude: $B_{rms} = 10pT \quad \mu = 0.76, \quad E = 9.3keV$
- Diffusion equation: $\frac{\partial f}{\partial t} = \frac{\partial}{\partial \mu} D_{\mu\mu} \frac{\partial f}{\partial \mu}$
- Obtain f and $\langle \Delta\mu^2 \rangle \quad \langle \Delta\mu^2 \rangle = \int \mu^2 f d\mu - \left(\int \mu f d\mu \right)^2$



- Pitch angle diffusion coefficients from TMP are consistent with quasilinear theory at small wave amplitude
- Electron distribution function f



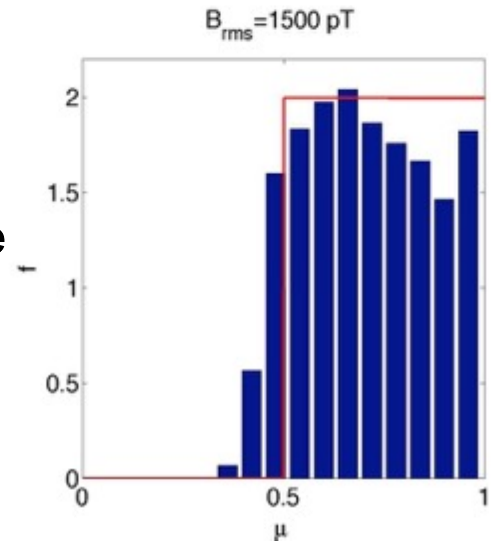
> It has a Gaussian-like distribution and f limit to the range of resonance pitch angles

> Whistler wave-electron resonance. The quasilinear pitch angle diffusion coefficient

$R_{k,\omega} \sim \delta(\omega - kv + \frac{n\Omega}{\gamma}) \Longrightarrow$ Delta function

Pitch angle diffusion at large wave amplitude

- The electron distribution f as a function of μ at wave amplitude $B_{rms} = 1500\,pT$



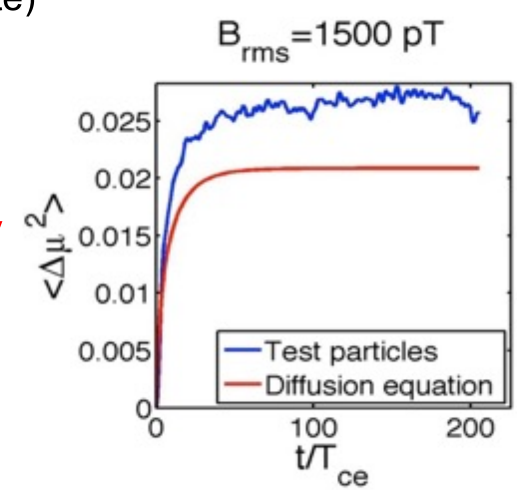
  - Whistler wave-electron resonance occurring at pitch angle range: $\mu \sim (0.5, 1)$

  But electron distribution function outside of the pitch angle resonance range: $\mu \sim (0.3, 0.5)$ ⇨ Why?

  - Resonance broaden theory (Dupree 1966)

$$R_{k,\omega} \sim \delta(\omega - kv + \frac{n\Omega}{\gamma} + \frac{i}{\tau_c})$$ ⇨ Lorentzian function

($1/\tau_c$ is wave-particle decorrelation rate)



  - Broaden resonance in $D^R_{\mu\mu}$ due to electron orbit perturbation, smoothing of electron distribution

- Pitch angle diffusion coefficients from TPM/QL theory

  - Enhanced diffusion rate from TPM comparing to quasilinear diffusion rate from QL theory

$D^{QL}_{uu} = 0$ at pitch angle $u = \cos\alpha \in (0, 0.5)$

Discussion

- Magnetic field geometry effect on the whistler-electron resonance in Earth's radiation belt.

  - It is more important for energy below 1Mev electron

- Breakdown of quasilinear theory : large wave amplitude

  - Comparison: Test Particle Model vs QL theory

  - The enhanced diffusion rate is due to resonance broadening

Part (II) Anomalous electron-ion energy coupling in tokamak plasmas

Net turbulent heating

Nonlinear electron-ion energy coupling

Motivation

- Transfer vs Transport

$$\frac{3}{2}n\frac{\partial T_\alpha}{\partial t}+\underbrace{\nabla\cdot Q_\alpha}_{\text{Transport}}=\underbrace{\langle\tilde{E}\cdot\tilde{J}_\alpha\rangle}_{\text{collsionless transfer}}\underbrace{\mp n\nu\frac{m_e}{m_i}(T_e-T_i)}_{\text{Collisional transfer}}+\ldots$$ heat balance; $\alpha=e,i$

$\rightarrow Q$ heat flux, energy loss by turbulent transport

$\rightarrow\langle\tilde{E}\cdot\tilde{J}_\alpha\rangle$

- turbulent heating for single species: electron cooling, ion heating
- electron and ion collisionless energy transfer, local energy "source" or " sink"

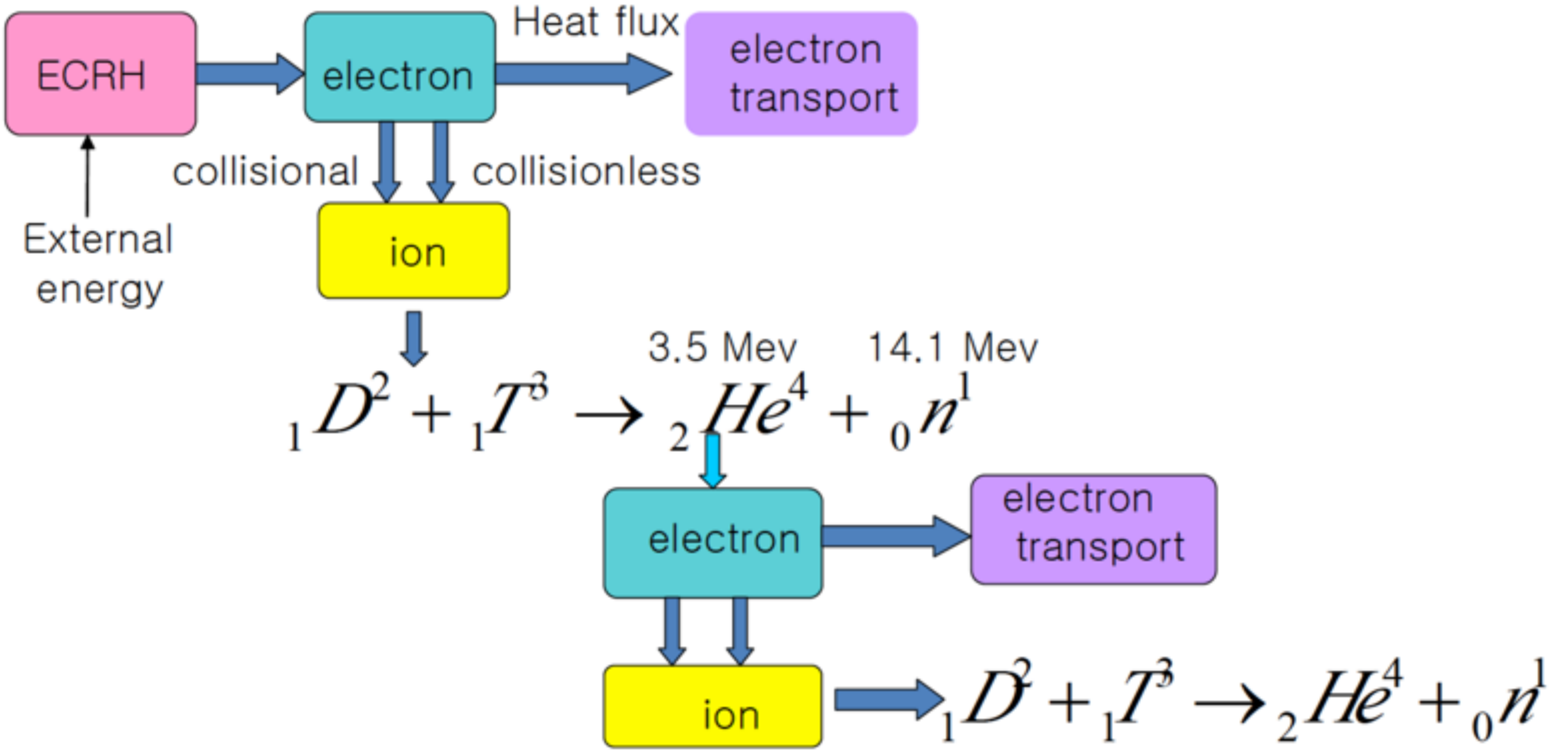
$\rightarrow\ \mp n\nu\frac{m_e}{m_i}(T_e-T_i)$: electron and ion heat transfer by collisions

★ ITER: *low collisionality, electron heated plasma*

- Collisionless energy transfer likely dominant!!

- ITER: collisionless, electron heated plasma

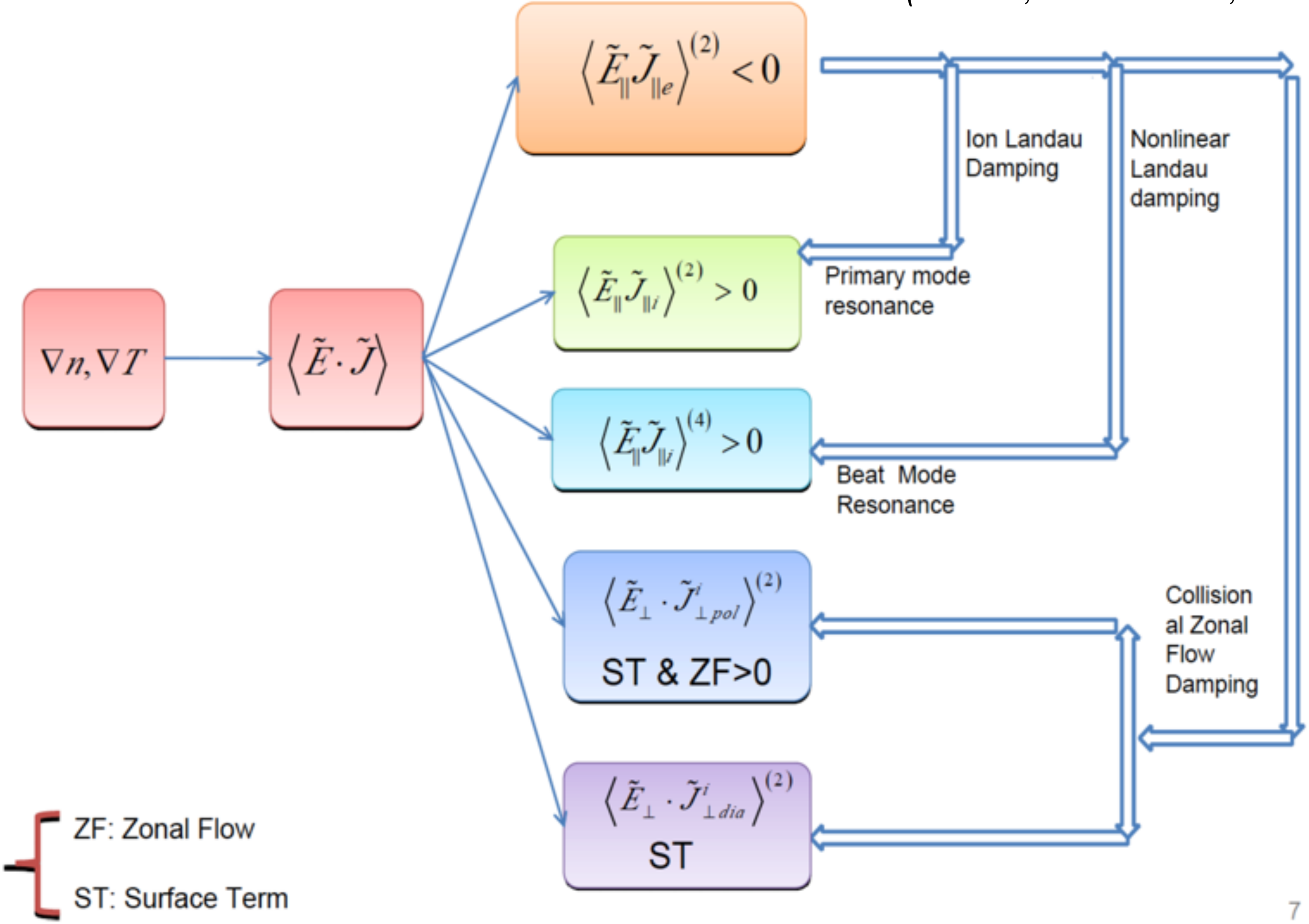
- Two stages in energy flow $\frac{3}{2}n\frac{\partial T_e}{\partial t}+\nabla\cdot Q_e=\langle \tilde{E}\cdot\tilde{J}_e\rangle - n\nu_{e,i}\frac{m_e}{m_i}(T_e-T_i)+\ldots$



- What is ultimate fate of the energy? ➡ Collisionless energy transfer mechanisms?

Turbulent Energy flow Channels

(L.Zhao, P.H.Diamond, POP, 2012)



- Necessary Correspondence: Nonlinear Saturation and Energy Transfer
  - Nonlinear saturation in turbulent state implies energy transfer from source $(\nabla T, \nabla n)$ to sink
  - Schematically, saturation implies some balance condition must be satisfied

i.e. $$0 = \gamma = \underbrace{\gamma_{\substack{Linear \\ electron}}}_{>0} + \underbrace{\gamma_{\substack{Linear \\ ion}}}_{<0} + \underbrace{\gamma_{\substack{Zonal \\ Flow}}}_{<0} + \underbrace{\gamma_{NLLD}}_{<0} + \ldots$$

  - Channels for electron → ion energy transfer **must** be consistent with saturation balance

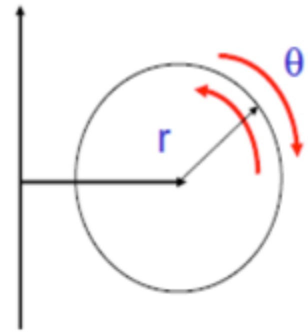
In particular:

- If zonal flows control saturation, they **must** contribute to energy transfer and dissipation.
- As zonal flows are nonlinearly generated (Reynolds stress), we should consider other nonlinear heating channels.

- What is a zonal flow ?

  $n = m = 0$ toroidally, poloidally symmetric

  $E \times B$ shear flow

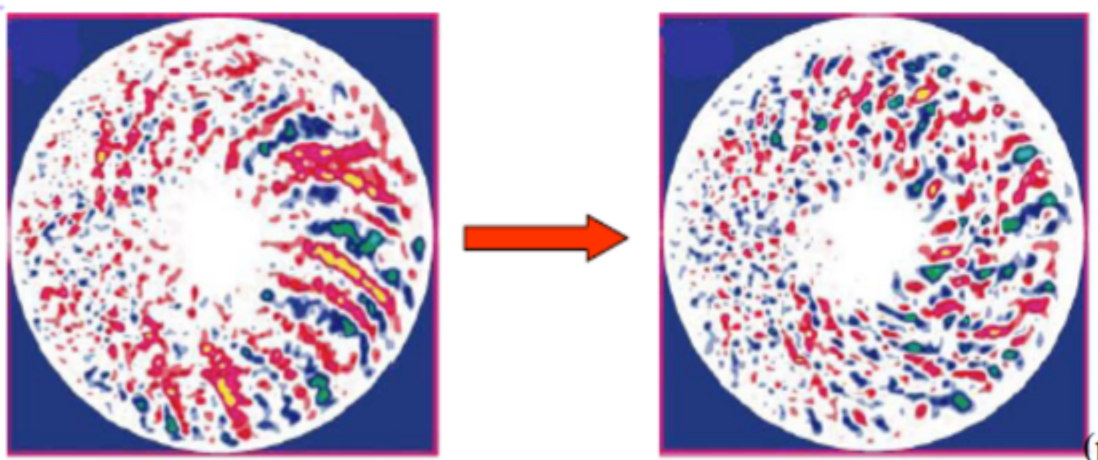


- How are zonal flows generated ?
  - Zonal flows are driven by Reynolds stress

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\frac{\partial}{\partial r}\underbrace{\langle \tilde{V}_r \tilde{V}_\theta \rangle}_{\text{Reynolds stress}} \underbrace{- \upsilon_{coll} \langle V_\theta \rangle}_{\text{Weak damping}}$$

(Rosenbluth & Hinton 98)

ZF shearing eddies



Lin 98

(poloidal contour shots)

turbulence without zonal flow with zonal flow

Quasilinear Turbulent Heating in Electron Drift Wave

(Prototype; CTEM- specific later)

- Calculate $\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\rangle^{(2)}$ in quasilinear theory
  - DKE for electron
  - Take non-adiabatic electron distribution function

$$\tilde{g}_k = \frac{(\omega_* - \omega)}{\omega - k_z v_z}\frac{e\tilde{\varphi}_k}{T_e}\langle f_e\rangle, \quad \omega_{*e} = \frac{k_y \rho_s c_s}{L_n}, \quad \langle f_e\rangle \text{ is Maxwellian}$$

- $$\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\rangle^{(2)} = e\int dv v_z \tilde{E}_z \tilde{g}_k = \sum_k \pi n T_e \left|\frac{e\tilde{\varphi}_k}{T_e}\right|^2 \frac{\omega}{|k_z| V_{the}}(\omega - \omega_{*e})\langle f_e\rangle_{\frac{\omega}{k_z}}$$

  - $\omega = \dfrac{\omega_{*e}}{1+k_\perp^2\rho_s^2}$, $\quad \langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\rangle^{(2)} < 0$ **the electrons cool via inverse electron Landau damping**

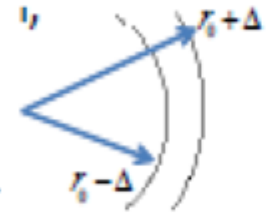
- Similarly, calculate $\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\rangle^{(2)}$ for ion

- $$\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\rangle^{(2)} = \sum_k \pi n T_i \left|\frac{e\tilde{\varphi}_k}{T_i}\right|^2 \frac{\omega}{|k_z| V_{the}}\left(\omega + \frac{T_i}{T_e}\omega_{*e}\right)\langle f_i\rangle_{\frac{\omega}{k_z}}$$

  - $\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\rangle^{(2)} > 0$, **the ions gain energy via ion Landau damping**

<u>Perpendicular</u> Current Induced Turbulent Heating

- The turbulent heating induced by ion polarization current
  - $\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = -\left\langle \vec{\nabla}_\perp \cdot \left(\tilde{\varphi} \tilde{J}^{pol}_{\perp i} \right) \right\rangle + \left\langle \tilde{\varphi} \vec{\nabla}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle$
  - Defining a annular region $\langle \ldots \rangle = \int_0^{2\pi R} dz \int_0^{2\pi} r d\theta \int_{r_0-\Delta}^{r_0+\Delta} (\ldots) dr$



- Perpendicular heating ⟺ Reynolds work on zonal flow

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = n m_i A \left(\underbrace{\langle V_\theta \rangle \langle \tilde{V}_r \tilde{V}_\theta \rangle \Big]_{r-\Delta}^{r+\Delta}}_{\bullet\ \text{wave energy flux}} - \underbrace{\int_{r-\Delta}^{r+\Delta} dr \langle V_\theta \rangle \frac{\partial}{\partial r} \langle \tilde{V}_r \tilde{V}_\theta \rangle}_{\bullet\ \text{Directly linked to zonal flow drive}} \right)$$

- At steady state

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = \int_{r-\Delta}^{r+\Delta} dr \upsilon_{col} \langle V_\theta \rangle^2 > 0,$$

➡ Zonal flow frictional damping is the final fate of net electron-ion energy transfer

- other damping possible

- Diamagnetic <u>current induced</u> turbulent heating

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{Dia}_{\perp i} \right\rangle = -nc\tilde{\varphi} \frac{B \times \nabla \tilde{p}}{B^2} \Big]_{r-\Delta}^{r+\Delta}$$

➡ Heat flux differential

Basic comparison of channels

(L.Zhao, P.H.Diamond, POP, 2012)

ITER Parameters R=6.2m, a=2m,q=2	
$Ratio = \dfrac{\langle \tilde{E}\cdot\tilde{J}\rangle_i}{\langle \tilde{E}\cdot\tilde{J}\rangle_e}$	Short wavelength $k_\perp \rho_s \sim 1$
$\langle \tilde{E}\cdot\tilde{J}\rangle_i^{(2)}$	1.56×10^{-2}
$\langle \tilde{E}\cdot\tilde{J}\rangle_{pol}^{(2)}$	$0.8\nu_*$

★ *Ratios of energy dissipation channels at different collisionality*

Ion Landau Damping

Zonal flow friction

$\nu_* = 10^{-3}, \rho^* = 10^{-3}$ $\nu_* = 10^{-2}, \rho^* = 10^{-3}$

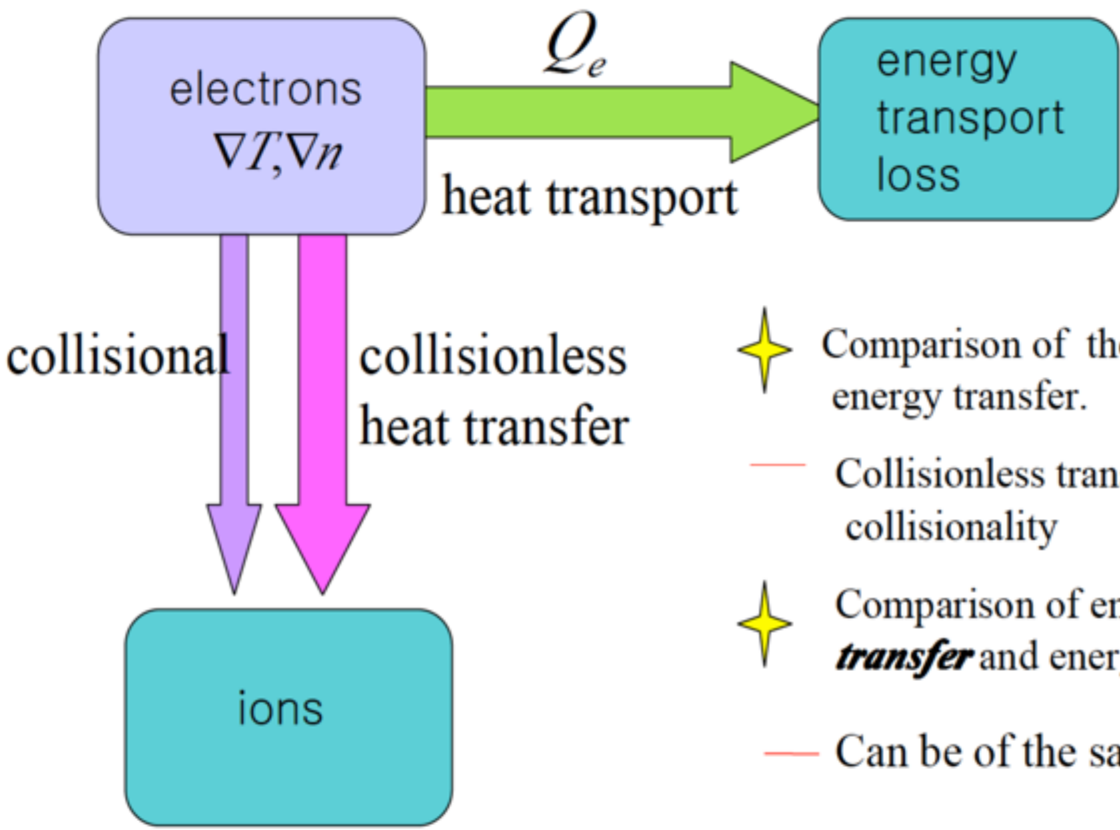
★ Zonal flow frictional damping can be a significant dissipation channel

★ "Collisionless drift wave" $\omega \gg \nu_* > 0$

Implication → Bottom Line

- Electron turbulent energy transport

$$\frac{3}{2} n \frac{\partial T_e}{\partial t} + \nabla \cdot Q_e = \left\langle \tilde{E} \cdot \tilde{J}_e \right\rangle - n\nu \frac{m_e}{m_i}\left(T_e - T_i\right)$$ → Electron heat balance



- Comparison of the collisional and collisionless energy transfer.
  - Collisionless transfer can dominate at low collisionality
- Comparison of energy transfer in collisionless ***transfer*** and energy ***transport*** by heat flux Q
  - Can be of the same order!

Collisionless vs collisional energy transfer

- Collisonality ν_* in ITER
  - dimensionless $\nu_* = \dfrac{\varepsilon^{-3/2} Rq\nu_e}{V_{the}}$ $\Rightarrow$ $\nu_* \sim 10^{-3}$
- Collisionality at crossover of collisional and collisionless coupling
  - Energy transfer in collision : $Q_i \simeq n_e \dfrac{m_e}{m_i} \nu_e T_e \left(1 - \dfrac{T_i}{T_e}\right)$
  - Quasilinear trapped electron cooling in CTEM

$$\left\langle \bar{\tilde{E}} \cdot \bar{\tilde{J}}_e \right\rangle_b^{(2)} \simeq 4\pi^{1/2} \varepsilon^{1/2} n T_e \left(\frac{R}{2a}\right)^{3/2} \rho_*^2 \left(\omega - \omega_*\right) \langle f_e \rangle \rrbracket_{E = \frac{\omega}{k_\theta} \frac{RT_e}{\rho_s C_s}}$$

  - **At crossover** : $Q_i \approx \left\langle \bar{\tilde{E}} \cdot \bar{\tilde{J}} \right\rangle_b^{(2)}$ $\Rightarrow$ $\nu_* \sim 10^{-3}$

☆ The collisonless turbulent energy transfer is equal to collisional inter-species coupling process!

☆ As T_i close to T_e, collisionless process will control electron-ion transfer in ITER

Transfer vs Transport

- The transfer and transport energy loss in CTEM
  - Compare the volume integral of the electron cooling to the surface integrated of the electron heat flux

$$A\tilde{Q}_e\rrbracket_{boundary} = \int d^3 r \left\langle \tilde{E}\cdot\tilde{J}\right\rangle$$

  - The heat flux for electrons : $\tilde{Q}_e = \left\langle \tilde{v}_r \tilde{P}_e \right\rangle = -\frac{c}{B}\sum_k k_\theta \,\mathrm{Im}\,\tilde{P}_e^{(1)}\tilde{\varphi}$
  - The pressure fluctuation $\tilde{p}_e^{(1)} = \int d^3 v \frac{1}{2} m v^2 \bar{\tilde{g}}_b$

$$\tilde{Q}_e = \sum 4\pi^{\frac{1}{2}} \varepsilon^{\frac{1}{2}} \left(\frac{R}{L_n}\right)^{\frac{5}{2}} \left|\frac{e\bar{\tilde{\varphi}}}{T_e}\right|^2 \frac{V_{the}^2 k_\theta n T_e}{\Omega_e} (\omega - \omega_{*n}) \langle f_e \rangle \rrbracket_{E=\frac{\bar{\omega}_{de} R T_e}{\omega_* L_n}}$$

★ The ratio

$$\frac{\Delta r \left\langle \tilde{E}\cdot\tilde{J}\right\rangle}{\tilde{Q}_e\rrbracket_{boundary}} \approx 2\frac{a}{R} \sim o(1)$$

The rate of electron energy lost by collisionless energy transfer is comparable to turbulent transport by CTEM !

- A new perspective for electron thermal transport experiments

- Electron and ion energy balance with/without turbulent energy transfer

	Heat transport without transfer	Heat transport with transfer	Comparison
Heat balance equation	$\partial_t T_\alpha + \nabla \cdot Q_\alpha = S$	$\partial_t T + \nabla \cdot Q_\alpha = \left\langle \tilde{E} \cdot \tilde{J} \right\rangle_\alpha + S$	$\left\langle \tilde{E} \cdot \tilde{J} \right\rangle_\alpha \neq 0$
Electron heat flux	$\nabla \cdot Q_e = S$	$\nabla \cdot Q'_e = \left\langle \tilde{E} \cdot \tilde{J} \right\rangle_e + S$	$\left\langle \tilde{E} \cdot \tilde{J} \right\rangle_e < 0$
Ion heat flux	$\nabla \cdot Q_i = S$	$\nabla \cdot Q'_i = \left\langle \tilde{E} \cdot \tilde{J} \right\rangle_i + S$	$\left\langle \tilde{E} \cdot \tilde{J} \right\rangle_i > 0$
Electron thermal diffusivity χ_e	$\chi_e = -Q_e / n\nabla T_e$	$\chi'_e = -Q'_e / n\nabla T_e$	$\chi_e > \chi'_e$
Ion thermal diffusivity χ_i	$\chi_i = -Q_i / n\nabla T_i$	$\chi'_i = -Q'_i / n\nabla T_i$	$\chi_i < \chi'_i$

(L. Lin 2009)

Result and discussion

- A theoretical model of anomalous electron-ion energy coupling Form was constructed in this work.

$$\left\langle \tilde{E}\cdot \tilde{J}_{\alpha}\right\rangle = A_{L}^{\alpha} I + B_{NL}^{\alpha} I^{2} + C_{ZF}^{\alpha} I^{2} \qquad \alpha = i,e$$

- The energy transfer can be through linear and nonlinear wave-Particle interactions and turbulence-zonal flow interactions.

  - Net turbulent heating

- In ITER plasma, the collisionless energy transfer can dominant the energy coupling process. It is same order as the turbulent transport. We need consider the influence of the collisonless energy coupling in the total energy transport model.

Conclusion

- Two applications of the wave-particle interaction:

Space plasma:

- We calculated bounce-averaged diffusion coefficients in a storm condition to understand the energetic particle dynamics.
- The magnetic field geometry enters as an important factor in wave-particle resonance.

- Test Particle Simulation : large wave amplitude

Tokamak plasma:

- A theoretical model of anomalous electron-ion energy coupling be built up.
- The collisionless energy transfer can through not only wave-particle interaction but also turbulence-zonal flow Interaction.